

Characterization and Evaluation of Lunar Regolith and Simulants

Final White Paper

Dr. William M. Cross

ESMD Faculty Fellowship,

Overview documenting implementation experience providing details to help others implement a similar ESMD senior design project(s)

A paper documenting the implementation experience and published in the June 2010 (Louisville, KY meeting) American Society for Engineering Education Proceedings is included in Appendix A.

An overview of the implementation from this work, which included several projects in addition to the NASA project, is given in the conclusions section of this paper and repeated below:

The samurai-type sword design projects have been greatly helped by incorporating systems engineering design principles into the MME design curriculum. The enhanced communication and more explicitly specified requirements and constraints have resulted in the overall design process being 4-5 months ahead of 2008-09, although some of this increase is related to the experience gained by the students during the 2008-09 design. These groups have completed their preliminary and critical design reviews and are currently performing the chosen designs.

The NASA ESMD design project is slightly behind this pace due to the difficulties encountered in the characterization of the mineral samples. Despite this delay, utilization of systems engineering design principles has made implementing the new design project easier as compared to the 2008-09 projects. Also, the students have a better understanding of what is required of the design and of them.

Overall, regardless of the structure of the design projects, the utilization of system's engineering principles has proved a valuable addition to the MME design courses and will likely continued to be utilized.

Assessment Plan results

The assessment plan was divided into three primary areas; Accreditation Board for Engineering and Technology (ABET) assessment, student surveys, external review.

ABET

The Department of Materials and Metallurgical Engineering (MME) uses junior and senior design coursework in several areas of assessment. For this work, the assessments used are based on final design reports, final oral reports and design fair posters. Evaluations were performed in five of the eleven ABET assessment areas. These areas were c) Optimally select material and design materials treatment and production processes (d) Function well on teams (f) Know professional and ethical responsibilities and practices (g) Communicate effectively (h) Know engineering's global societal context. Table 1-5 contain the results from these evaluations

Table 1. Optimally Select Materials and Design Processes, ABET Criterion C

	Final Written Report	Final Oral Report
Understand Design Process	2.6	4.6
Formulate Engineering Solutions	4.2	4.5
Master Iterative Design Process	3.4	4.5
Recognize and Observe Constraints	3.4	4.7

Table 2. Function Well on Teams, ABET Criterion D

	Student Self Evaluation	Student Group Evaluation	Final Written Report
Responsible Participation	4.2	3.9	3.4
Interaction Skills	4.2	3.9	3.4
Assimilation and Receptiveness	4.3	4.0	3.4

Table 3. Know Professional and Ethical Responsibilities and Practice, ABET Criterion F

	Final Written Report
Carries Out Responsibilities Professionally and Ethically	4.2
Understands Basic Engineering Principles and Practices in Terms of Professional Ethics and Behavior	4.2

Table 4. Communicate Effectively, ABET Criterion G

	Design Fair Poster	Final Design Report
Effective Presentation	4.9	3.8
Organization and Styles Consistent with Professional Practice	4.9	3.8
Understands Audience and Room Limitations	3.0	3.8

Table 5. Know Engineering's Global and Societal Context, ABET Criterion H

	Final Written Report
Have the Broad Education Necessary to Understand Global and Societal Context	3.4
Awareness of Contemporary State of Knowledge and Its Relation to Design	4.2
Recognition of Need for Life-Long Learning	4.6

Tables 1-5 show that the students generally the student assessments were very positive in the student's ability to engage in Metallurgical/Materials Design. The primary area of concern was the final written reports were weak in indications showing the students understood the design process. As the final oral presentations were not weak in this area, this may indicate that the paper format was not set up to highlight this point as the reports were more focused on results/achievements than on process. The details of the process were generally contained in weekly/monthly reports than in the final report.

ABET criterion C is most directly related to the systems engineering process. Figure 1 shows the assessment by criterion C from 2002-2009. This data is not completely comparable to that in Table 1, as the results from two of the assessment tasks have not been gathered yet, but the results are similar to and generally a little higher than previous years assessments.

By utilizing a more codified set of processes to introduce engineering design principles and the systems engineering process, these assessments are expected to stay the same or increase in mean performance and lead to lesser year-to-year variation by minimizing the majority of variation outside of having different sets of students each year.

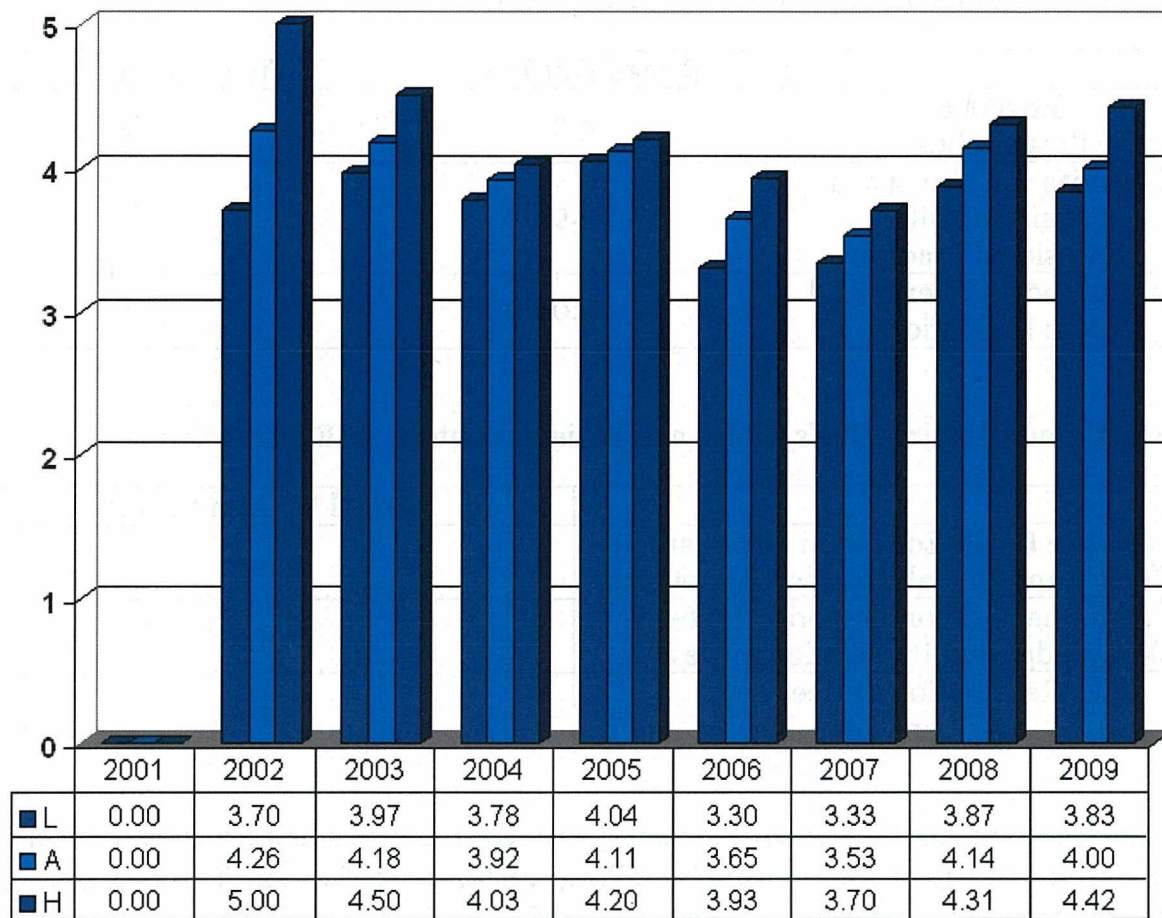


Figure 1. Summary of yearly data from ABET Criterion C ,2002-2009.

Student Surveys

Students who participated in both were questioned about the design experience and how the implementation of systems engineering design principles worked for them. The replies received are contained below.

Student 1, not in NASA Design Group

I cannot really say much for the moon dust project, but as for the other design groups I have to say that doing a group update/paper really left work to those who knew the most about the subject. It became more of a "let so and so do it since they have the info/product" I dont want to say design needs more work out of the students, but I felt that work, report wise, was left mainly to one to two people both years of design. So my suggestion is to have group updates but have each person write their own

technical paper, that way each person has to take part in the labor part of design as well as the mental work of learning throughout the project.

Student 2, not in NASA Design Group

So far as customer requirements/matching design to customer requirements go, I think there needs to be improved communication between the teams. Granted there were design review meetings throughout the year, but sometimes it was often hard to match what the customer wanted, because sometimes it seemed that we weren't sure what our customer wanted. So far as matching design to customer requirements - I think my team did what we could, with what resources and time we had. We might have been able to produce the quality iron that our customers were in need of, but our financial situation, as well as what time we were allotted, wasn't much to help us achieve our ultimate goal.

Lessons learned were how to practically apply metallurgical trends and knowledge in steelmaking. I personally learned how to be more vocal with my opinions over the year. That might sound bad, but being a female engineering major, I've learned that males tend not to listen to what females have to say, or often just ignore what we contribute to a project. While working on the junior and senior design projects, I've learned to be more vocal in my opinions, and if I am discredited then I need to be more obstinate in my opinion and have metallurgical backup to what I say.

There is always room for improvement, and hopefully that'll come next year in the form of increased communication between the teams.

Student 3, in NASA Design Group

The adoption of the systems engineering format and customer requirements to Junior/Senior Design served the project well. By having a specific customer, we gained not only a more narrow focus, but were able to receive specific answers to specific questions for the direction of the design.

In retrospect, the lunar regolith simulant group should have taken advantage of this communication option even more often than required.

Within the lunar regolith simulant group there was a complete lack of structure. There existed no defined group leader or schedule. Work was accomplished only as members rose to the task, with little communication between group members. While several group members did put in significant work, others were allowed to coast by with little to no

contributions. The institution of a design leader would not only ensure all members were contributing, but also that the design was developing on schedule.

External Review

An external review of the design process and results was requested from experts within the field were solicited. The reply received is contained below.

The student design report was very thorough from a mineral processing perspective. A wide breadth of mineral concentration techniques were evaluated. Data analyses too were very complete and reasonably well interpreted. The students captured the essence of the iterative nature of the design process from a mineral processing perspective, which is often not straightforward. Missing components that were noted included a listing of the chemical compositions of the minerals in question and a list of references.

Dr. Jon J. Kellar
Douglas Fuerstenau Professor and Department Head of Materials and Metallurgical Engineering
South Dakota School of Mines and Technology
501 E. St. Joseph Street
Rapid City, SD 57701-3995

Final Senior Design Project(s) Results

The final design report is given in Appendix B. The objectives were to investigate mineral processing methods to produce mineral separates (having >80 wt% primary mineral) of high-calcium plagioclase, orthopyroxene and clinopyroxene using material obtained from relevant mines, particularly the Stillwater Complex in Montana. Two samples were obtained, one of mill sands already processed in the mill and a second of norite from a road above the mine site. The mill sand contained high-calcium plagioclase and glass smelter slag. These were separated magnetically, but the final grades (amount of each mineral) could not be determined due to the amount of glassy material. Further, the absence of any pyroxenes made this material less than ideal for the current project.

The road norite material contained all three mineral types. The goal from the technical expert was to achieve at least 80 wt% grade of each mineral in a concentrate. This was achieved at all sizes tested above 37 microns for high-calcium plagioclase and orthopyroxene. There was very little clinopyroxene in the sample making its concentration more difficult. A free fall electrostatic separator was built, and showed initial promise, but results were not finalized prior to the end of the semester. These results will be finished during the summer or as part of a similar design in the new academic year.

Information to help others further develop Senior Design Project(s) Results (if applicable)

I do not have any additional information for this area.

Additional findings

Many NASA projects are very interesting to a variety of audiences. Take advantage of all these possibilities. I gave a seminar to relevant NASA personnel, a seminar and a class at the University of Utah, gave talks and/or posters at three professional society national and regional meeting covering my field, Metallurgical Engineering; a related field, Geological Engineering; and Engineering Education. Finally, I spoke to more general audiences through and interview on South Dakota Public Radio and to a group of middle school students attending a week-long space camp on my campus.

This is an excellent program and more people knowing about it through dissemination in many different venues will only help increase the strength of the program.

Lessons Learned

Communication is critical to the success of the design effort. For the designs that required intergroup communication this worked much more smoothly when compared to similar efforts the previous year. Communication within groups is more difficult to judge. Clearly, there were some problems, particularly with the size of the NASA group (7 students). The issue tracking procedure I tried to implement did not work particularly well and I think was not well understood by the students. For larger groups a designated team leader who is in charge of tracking the design efforts, in retrospect, would have helped.

Appendix A

American Society for Engineering Education Paper

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NASA Senior Design: Mineral Separation Technology for Lunar Regolith Simulant Production

Abstract

A NASA-ESMD (National Aeronautics and Space Administration-Exploration Systems Mission Directorate) funded senior design project “Mineral Separation Technology for Lunar Regolith Simulant Production” is directed toward designing processes to produce simulant materials as close to lunar regolith as possible. The eight undergraduate (junior and senior) students involved are taking a systems engineering design approach to identifying the most pressing concerns in simulant needs, then designing subsystems and processing strategies to meet these needs using terrestrial materials. This allows the students to, not only learn the systems engineering design process, but also, to make a significant contribution to an important NASA ESMD project.

This paper will primarily be focused on the implementation aspect, particularly related to the systems engineering process, of this NASA EMSD senior design project. In addition comparison of the NASA ESMD group experience to the implementation of systems engineering practices into a group of existing design projects is given.

Introduction

Prior to the discussion of the implementation of system’s engineering into engineering design, a brief background on the curricular structure of the Materials and Metallurgical Engineering (MME) department and how the design courses fit into the curriculum is given.

MME Course Stream

The design courses are structured to integrate material learned in core courses with the solution of problems within the field. Typically, students enter the design courses in their junior year having taken two core classes – Introduction to Mineral Processing and Properties of Materials. Both of these are three hour lecture and one hour laboratory courses. During their junior year, MME students primarily take discipline specific classes, usually 7-11 credit hours per semester. The courses and hours taken are variable as the MME department is relatively small, ~20 students per year, and the upper division classes are offered on an every other year basis to ensure that the number of students in each course is of sufficient size to meet minimum size requirements¹.

Design Stream

Beginning in the 2008-09 academic year, the Department of Materials and Metallurgical Engineering (MME) at the South Dakota School of Mines and Technology revamped the design curriculum. The design curriculum consisted of MET 351—Engineering Design I and 352—Engineering Design II for juniors and MET 464—Engineering Design III and MET 465—Engineering Design IV for seniors². The purpose and objectives of these classes can be summarized by the following Accreditation Board for Engineering and Technology (ABET) self-study description³.

This is a two-course sequence in Interdisciplinary Senior Capstone Design Project (ISCDP) that involves both lecture and design practice sessions. The course integrates vertically and horizontally concepts from all areas of Metallurgical Engineering into a practical senior capstone design project design to train the students in the design practice. Fundamentals of the design process, specifications, decision-making, materials selection, materials process, experimental design, statistic process control and preliminary design are the focus. The major part of this course consists in the development of the senior capstone design project.

Thus, the students are expected to understand how to perform materials selection and optimally select material processes to accomplish a year-long design project. As stated, the courses are a mixture of lecture and design session. In general, the design portion focused primarily on faculty-mentored design experience⁴⁻⁷. In many ways, the overall process is similar to some aspects of axiomatic design⁵, as the lectures (and associated assignments) focus on a few basics that are designed to ensure that all students have the requisite knowledge to significantly contribute to the design projects rather than to differentiate students by their abilities and lead quickly to the more active learning areas of the design project. In addition, studying portions of the design process through case studies was used, particularly in the junior design courses (MET 351 and 352), to further understanding of how engineering design works. Overall, a variety of pedagogical techniques are utilized in order to reach all students, as students do not respond equivalently to different teaching strategies.

Prior to 2008-09, these courses were separate courses with MET 351 and MET 352 being focused on juniors learning the basics of the design process, particularly with respect to material selection processes, interaction of materials, and materials processing. In addition, teaming, ethics and global/societal concerns were also emphasized. Much of this work was performed through case studies and writing assignments. For MET 464 and MET 465, the seniors generally had two types of experiences, small groups led by an MME faculty member working on a metallurgy-based focus, or individual students working on multi-disciplinary teams, usually with groups sponsored through the Center of Advanced Manufacturing and Production

(CAMP)⁸. CAMP projects typically involve vehicles and provide a student-oriented, hands-on design and engineering experience⁸. These projects generally worked well, but individual student experiences varied widely, which was considered to be suboptimal for those students whose experiences were at the lower end and for the continuous improvement in departmental offerings expected by the ABET. In particular, the final design reports and design fair presentations of the students in MET 465 are major contributors to the MME department's outcome assessments. MET 465 is a primary source for assessment in areas c (optimally select material and design materials treatment and production processes), d (function well on teams), f (know professional and ethical responsibilities and practices), g (communicate effectively), and h (know engineering's global societal context)⁹.

The desire to improve the design experience led to revamping how the MME design courses were delivered. Essentially, a large design project composed of multiple parts and combining both the juniors and seniors was developed by the MME faculty. In the first year of the modified design sequence, the overall design project aimed at manufacturing a samurai-type sword from local Black Hills iron ore¹⁰. Four groups, composed of 5-8 students, were formed. These groups were: 1) agglomeration, 2) furnace manufacturing and steel production, 3) forging and drawing, and 4) forging and quenching. Each group was dependent on the results of the previous group for the final sword production. The experiences of the 2008-09 MME design were enlightening for both the students and faculty¹⁰. From the faculty perspective, the need for better management of communication between groups as the project structure was such that the primary customer for each group was another of the design groups. The lack of inter-group communication led to many difficulties, particularly with respect to deliverable timelines, material size, shape, composition and quantity. Thus, improving the overall design process was deemed critical to successful future design project implementation.

As the design for 2008-09 was winding down, the author was awarded a National Aeronautics and Space Administration (NASA) Exploration Systems Mission Directorate (ESMD) Faculty Fellowship. This fellowship, which is described in more detail below, included a requirement that NASA systems engineering design be incorporated into the senior design project funded. This requirement offered an excellent method by which the communication issue between groups could be addressed.

ESMD Faculty Fellowship

The stated purpose of the ESMD Faculty Fellowship program *“is to prepare faculty to enable their students to complete senior design projects with potential contribution to NASA ESMD objectives.”*¹¹ When applying for this program, a design project area related to a NASA ESMD program objective is chosen from the list included with the program solicitation and a short proposal for a senior design project submitted.

To develop the design project, the chosen faculty fellow travels to the NASA center of the NASA technical expert who had proposed the NASA EMSD project area and works with this technical expert for six weeks to help focus the design. The design proposal area was lunar and planetary systems and the specific project area being development, characterization and evaluation of lunar regolith and simulants.

As part of the grant, the faculty fellows also were part of the review team for another ESMD Space Grant Education project concerning the development of a fully implementable design course. For the 2009 faculty fellows, the reviewed course was developed by Dr. Stephen Whitmore (Utah State University, Department of Mechanical and Aerospace Engineering). While at the site of the technical expert, the initial portion of the review involved evaluating the slides Dr. Whitmore had developed for his year-long course entitled “Design and Testing of a Demonstration Prototype for Lunar/Planetary Surface Landing Research Vehicle”¹².

Implementation

The implementation phase of the NASA ESMD faculty fellowship began with the MET 351 and MET 464 students ranking their interest in the five design projects, four of the projects were continuations from 2008-09 concerning the samurai-type sword, and the other project was the author’s Mineral Separation Technology for Lunar Regolith Simulant Production faculty fellowship project. For the samurai-type sword groups, the agglomeration group has four collegiate members and one high school participant. The furnace group has six collegiate members, the forge-drawing group and forge-hammering group each have five collegiate members. The NASA ESMD group originally had eight collegiate members, but one participant changed majors and decided not to participate further in the project.

General

The first step in implementing NASA systems engineering design principles into the MME design projects was a lecture by the author to acquaint the MME students with the systems engineering process¹²⁻¹⁷. While systems engineering is increasingly becoming a critical part of many engineering disciplines, its scope is also very large. As such, a 50 minute presentation is not sufficient time to cover all of systems engineering.

Therefore, this presentation was focused on three main areas: requirements analysis, trade studies and design reviews. The manner in which requirements analysis proceeds is shown in Figure 1. The process begins in the upper right hand corner with determining the design requirements and constraints. These requirements and constraints can come from a variety of areas including the customer and other stakeholders, assumptions inherent in the process, legacy utilization, operational standards and governmental regulations and laws.

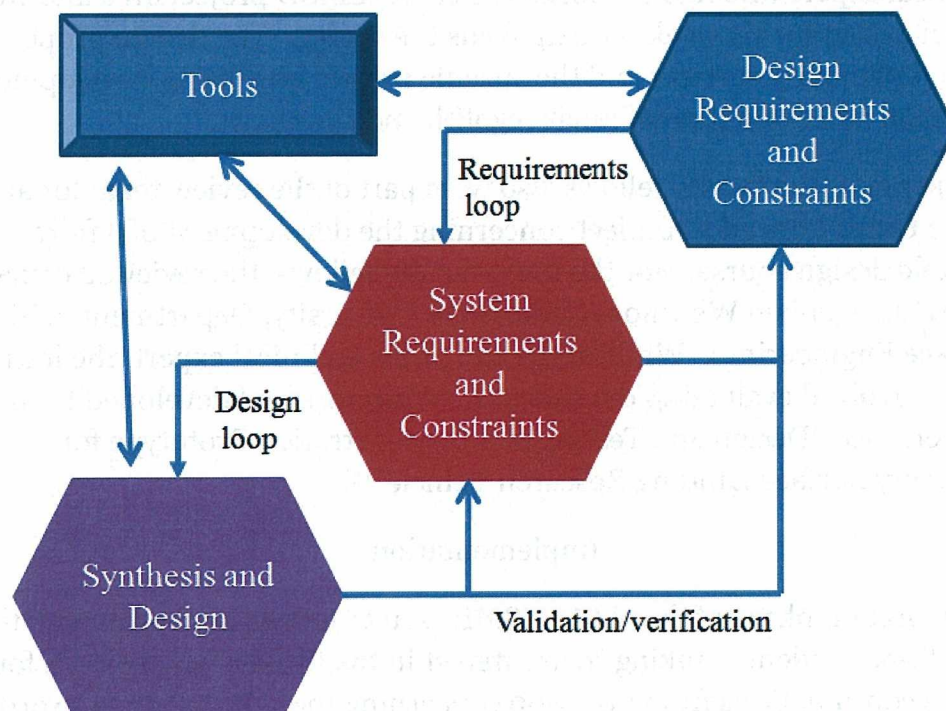


Figure 1. The systems engineering process. After Whitmore¹² and Guerra¹³.

The system requirements are derived from the design requirements and are used to understand the design requirements and how these requirements affect the system function. The systems requirements then feed into the design loop to engender possible design solutions. The possible solutions are evaluated by trade studies using design matrices to semi-quantitatively score the various designs. The designs are also validated/verified against the original customer requirements and constraints to ensure that the design fulfills its original goals. The validation and verification is tested through preliminary and critical design reviews. One other key to the satisfactory accomplishment of the systems engineering process is the formal tracking of actions and requests for information within and between groups and customers. Formal tracking is important as without this many tasks don't get finished. Without having a group

member in charge of finalizing the task's completion, other priorities occupy all group members and the task never is finished.

Requirements Loop

The first step taken was to identify the primary customer. For the samurai-type sword groups the primary customer was the next group, as defined previously. This created some initial concerns, as the requirements needed to flow from the higher number groups to the lower number groups, so that the requirements loop needed to be iterated several times to include the new system requirements occurring as each customer-group loop iterated. While some iteration was expected, keeping the communications flow between groups was an important task.

For the samurai-type sword groups, the agglomeration group requirements were derived from the furnace group who desired 150 pounds of iron ore pellets able to withstand the weight of the pellets and coke added to the furnace and having fluxing agents compatible with the refractory bricks used. The furnace group requirement, as given by the forging and drawing group, was to produce at least 10 pounds of low and high carbon steel. The primary requirement for the forge-drawing group is to fold and weld the low and high carbon steels produced by the furnace group, such that the forging-quenching group could form, weld and quench the drawn low and high carbon steel blanks into a samurai-type sword. The sword is made so that the ductile low carbon steel core supports the high carbon steel cutting edge. The forging and quenching group's primary customer was the MME faculty who required that the sword have a curve of the type common for samurai swords and have blade patterning similar to samurai swords.

For the NASA ESMD faculty fellowship group, the primary customer was the NASA technical expert. For this work, the technical expert indicated that processed ore from the Stillwater mine in Montana was of the greatest interest and that the final design should be able to produce up to a few hundred tons of lunar regolith simulant. Ideally, this would be accomplished by producing relatively pure mineral separates of each of the lunar regolith mineral constituents. In addition to the primary customer, possible secondary customers identified included a multi-disciplinary design team participating in the NASA ESMD Lunabotics Mining Competition. This group is interested in obtaining lunar regolith simulant material with which to practice for the competition, and a group of United States Geological Survey (USGS) scientists located in Denver, Colorado are interested in a possible simulant material (road norite) from an area adjacent the Stillwater mine. This material should be similar in composition to the Stillwater Mill Sand, but has not been processed in the mill, and, therefore, has a larger average particle size. Constraints found include the money available for testing and

characterization through the grant and the mineral processing equipment available within the MME department.

System Requirements

For the NASA ESMD project, the most important step toward understanding the system requirements and the tools by which the design can proceed, was obtaining and characterizing the simulant materials. Fifty pound buckets of Stillwater Mill Sand and road norite were obtained from the USGS scientists in Denver. X-ray diffraction and scanning electron microscopy characterization indicated several types of particles including olivine, anorthite, augite and some glass-like and hygrothermally altered materials. Further analysis is underway to identify the amount of each type of mineral in each size fraction. The size distribution of the Stillwater Mill Sand was determined using a nested sieve analysis. Analysis of the sieve data indicated that the five samples tested were quite similar and that the maximum size was approximately 125 μ m, which is a little small as compared to the maximum size of lunar regolith which typically is closer to 2-5 mm¹⁸. With this data, the design loop was begun.

Design Loop

Brainstorming of ideas considering how to use the tools available for mineral separations was performed to begin the process of evaluating the separation process designs. The separations considered were size separation by sieving, dense media separation based on the particle density, magnetic separation based on the magnetic susceptibility, electrostatic separation based on the surface charging in an electric field and flotation based on the ability of the mineral surfaces to be selectively rendered hydrophobic. Separations can be performed to maximize recovery, i.e. the total amount of desired material concentrated in the separation, or grade, i.e. the concentration of desired material separated. In addition, separations can be performed in series to optimize both recovery and grade. Magnetic separation has proved a viable method for separating the main non-magnetic components (anorthite), from the magnetic components (olivine, augite, enstatite). To separate the magnetic components, the most promising method is free-fall triboelectrostatic separation. A separator to perform triboelectrostatic experiments is currently being built.

Comparison of Samurai-Type Sword and NASA ESMD Experience

Initial comparison of the experiences of the five groups shows that using systems engineering practices seems to have improved the design experience for most students. The samurai-type sword groups initially exhibited the greatest benefit as many of the senior students were working on a similar project to their junior year. This allowed the design requirements to be more easily developed and the previous year's experience contributed to more immediate student buy-in to the use of system's engineering

principles. Also, members of the samurai-type sword groups being substantially similar to the previous year meant that many group dynamics issues had already been worked through. For the NASA ESMD group, there were only 3 seniors in the eight students and, as the project was new, no prior directly-relevant design knowledge existed within the group. This resulted in longer time for student buy-in to occur and for the group dynamics to become settled. Also, the previous group development in the samurai-type sword groups had led to the natural leader(s) within the group to assert their leadership. This was augmented by having each group designate a member to be part of an overall project group to ensure communication and the timing of deliverables occurred. For the NASA ESMD group, leadership did not emerge organically and, in retrospect, should have been developed by the faculty mentor at the start of the project.

Conclusion

The samurai-type sword design projects have been greatly helped by incorporating systems engineering design principles into the MME design curriculum. The enhanced communication and more explicitly specified requirements and constraints have resulted in the overall design process being 4-5 months ahead of 2008-09, although some of this increase is related to the experience gained by the students during the 2008-09 design. These groups have completed their preliminary and critical design reviews and are currently performing the chosen designs.

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Overall, regardless of the structure of the design projects, the utilization of system's engineering principles has proved a valuable addition to the MME design courses and will likely continued to be utilized.

Acknowledgements

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Appendix B
Final Design Report

Lunar Regolith Simulant Team

Brooke O'Bryan

William Ealy

Clinton Foster

Andrew Kelley

Nathan Saunders

Nicole Tramp

Adam Well

This work is part of a National Aeronautics and Space Administration (NASA) effort to develop terrestrial materials that effectively simulate the properties of lunar regolith. As few locations on Earth have the correct composition and concentration of minerals as the lunar surface, and the lunar surface itself varies from site to site, methods are needed to produce mineral separates of the lunar regolith simulant materials. These separates can then be combined to simulate any lunar site. This work aims to develop appropriate separation techniques.

The goal of the Lunar Regolith Simulant Team is to produce a lunar regolith simulant in a more efficient method than the current processes. This will be accomplished by separating the pyroxenes from the plagioclase. The primary customer for this project is Dr. Douglas Rickman and Dr. Jennifer Edmunson of NASA Marshall Space Flight Center. A broader customer base includes NASA and additional contracted companies concerned with vehicles, travel on, and settling of the lunar surface. The customer requirements are designing a separation process resulting in high concentrations (about 80%) of the minerals found on the lunar surface. The process must be reproducible on a large scale and cost efficient. Constraints within the design project include available equipment, availability of feed, budget, and time.

ID	Task Name	Start	Finish	Duration	Oct 2009				Nov 2009				Dec 2009				Jan 2010				Feb 2010				Mar 2010				Apr 2010			
					10/11	10/18	10/25	11/1	11/8	11/15	11/22	11/29	12/6	12/13	12/20	12/27	1/3	1/10	1/17	1/24	1/31	2/7	2/14	2/21	2/28	3/7	3/14	3/21	3/28	4/4	4/11	4/18
1	Teleconference	10/7/2009	10/7/2009	1d																												
2	Customer Requirements	10/7/2009	10/14/2009	6d																												
3	Preliminary Design Review	10/14/2009	11/4/2009	16d																												
4	Sample Arrived	11/12/2009	11/12/2009	1d																												
5	XRD/SEM Analysis	11/16/2009	11/23/2009	6d																												
6	Sieve Analysis	12/2/2009	12/4/2009	3d																												
7	CDR	12/7/2009	12/7/2009	1d																												
8	Separation Research	12/7/2009	1/15/2010	30d																												
9	Magnetic Separation Research	1/15/2010	2/10/2010	19d																												
10	Magnetic Separation	2/10/2010	3/22/2010	29d																												
11	Electro-static Separation	3/22/2010	4/30/2010	30d																												
12	Petrology	2/15/2010	4/30/2010	55d																												

The above schedule (Table 1) was constructed based on the progress of the group to show where the time and energy were spent in the project.

Source Material

Samples of the mill sands and the road norite from the Stillwater mine were obtained and prepared for mineralogical analysis. An initial test batch was prepared by separating representative samples from each feedstock, encasing the sample in a Bakelite pellet, polishing the sample, and examining the sample using optical microscopy and electron microscopy. The mill sands were found to be too difficult to examine optically in the metallography scope located in the polishing lab using the Bakelite sample due to their diversity. Better luck was had examining the road norite using the same process. This was due to the presence of only a handful of minerals in the road norite sample. The following image, Figure 1, taken with the metallography scope, clearly shows the pyroxenes-plagioclase boundary. The pyroxene is the lighter fraction with heavy cracking. Closer examination also showed the presence of twinning lines within the plagioclase further confirming its identity.

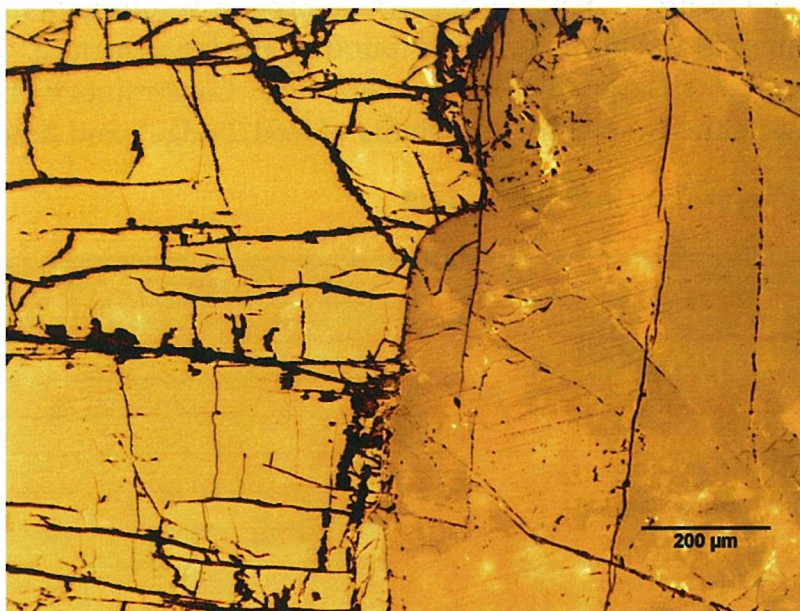


Figure 1: Pyroxene (left side)-plagioclase (right side) boundary

Additional work was also done using an optical microscope able to take color pictures, but the results yielded no additional information.

Electron microscopy (SEM) coupled with x-ray diffraction (XRD) analysis proved more useful. The two bakelight samples were both subjected to SEM and XRD work. The results showed that the mill sands contained a large amount of synthetic materials such as glasses and metals. This was the result of slag from the old smelting operation

being run through the current flotation circuit at Stillwater. The presence of these synthetics was previously unknown and may render the mill sands unsuitable as a source material. It was also found that there were relatively low amounts of pyroxenes present in the mill sands. The analysis of the road norite provided considerable insight into the mineralogy of the material. The following image, Figure 2, taken with the SEM shows an area containing both ortho- and clinopyroxenes as well as plagioclase and other altered minerals.

The shade of minerals in the Figure 2 is a function of the atomic weight of its constituents. The heavier the elements in a material, the brighter it appears in the picture. As a result, the plagioclase in this picture, which can be found on the left hand side, is lighter than the pyroxenes. Cracks can be seen permeating the pyroxene grain. These are believed to be the result of hydrothermal activity. Likewise, the bright specs in the cracks were determined to be iron hydroxides left behind after the water left. Additionally, the dark areas in the cracks were determined to be primarily hydrated clinopyroxenes. The brighter areas within the pyroxene grain were also found to be clinopyroxene while the majority of the matrix was found to be orthopyroxene. Small areas of altered plagioclase were also found on the surface of the pyroxene grain.

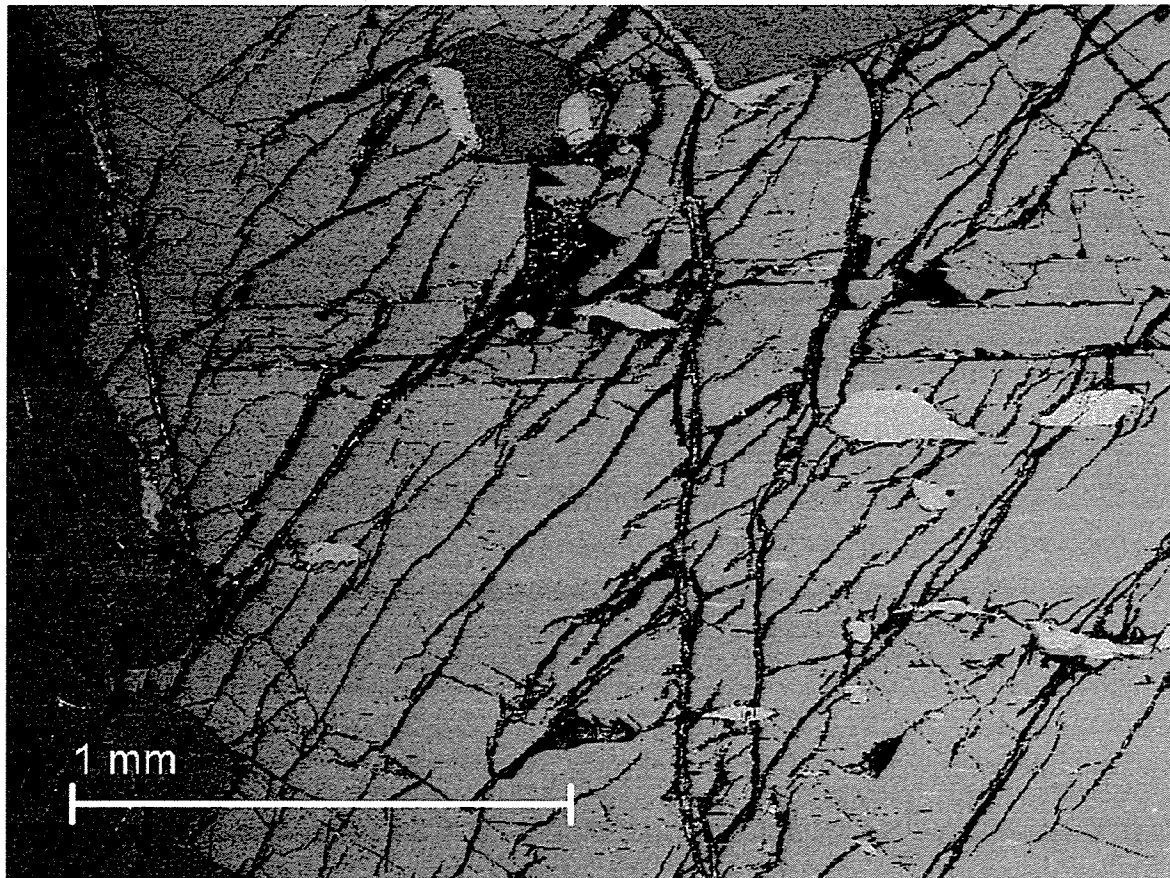


Figure 2: Road Norite SEM photograph

The presence of the small clinopyroxene grains, while not unexpected, does pose a potential problem for future separation of the pyroxenes. As can be seen, it will require substantial liberation to extract the small amounts of clinopyroxene from the orthopyroxene. This may prove to be prohibitively expensive. Additionally, the presence of the hydroxides may pose additional problems in creating a satisfactory simulant as there is very little water, and so hydroxide minerals, on the moon.

Thin sections of both the mill sands and the road norite were also prepared and examined using optical microscopy. Using polarizing light, the twinned nature of the plagioclase made it easy to differentiate from the pyroxenes as the plagioclase would show a banded texture that would change as the sample was rotated. Additionally, the presence of glass in the mill sand was shown again by the materials unchanging nature when the stage was rotated under polarizing light indicating a lack of crystalline structure.

Considered Designs

Several designs were considered for the separation of plagioclase, clino- and orthopyroxenes. Table 2 shows four different considerations and the appropriate numbers for each constituent that was needed for the final decision. The methods considered were: size separation, density separation, froth flotation, magnetic separation, and electrostatic separation.

Size separation

For this work, several representative samples of about 500 grams were prepared. Using a nest of sieves ranging from 8 mesh to 400 mesh. The stack of sieves was then placed into a mechanical sieve shaker for fifteen minutes. After the fifteen minutes, the remaining particles on each sieve were measured to the nearest 0.1 gram. The weights were totaled, and percentages were calculated for each sieve to the nearest 0.1%. Our data shows that five representative samples we had, separated in a similar way (see Figure 3).

Table 2: Mineral Processing Properties

Mineral	Density (grams/cm ³)	Isoelectric Point (pH)	Specific Magnetic Susceptibility (cm ³ /gram)	Electrostatic Voltage (Volts & Type)
Plagioclase	2.7-2.75 (anorthite)	2 (anorthite)	-0.39 x 10 ⁻⁶	6,240 & Neg.
	2.61-2.63 (albite)	2.6 (albite)	(anorthite)	(oligoclase)
Clinopyroxene	3.2-3.6 (augite)	2.7 (augite)	40-920 x 10 ⁻⁶	6,000 & Neg. (pyroxene, RSiO ₃)
Orthopyroxene	3.1-3.3 (enstatite)	2-2.5	80-1800 x 10 ⁻⁶	7,800 & Neg. (enstatite)

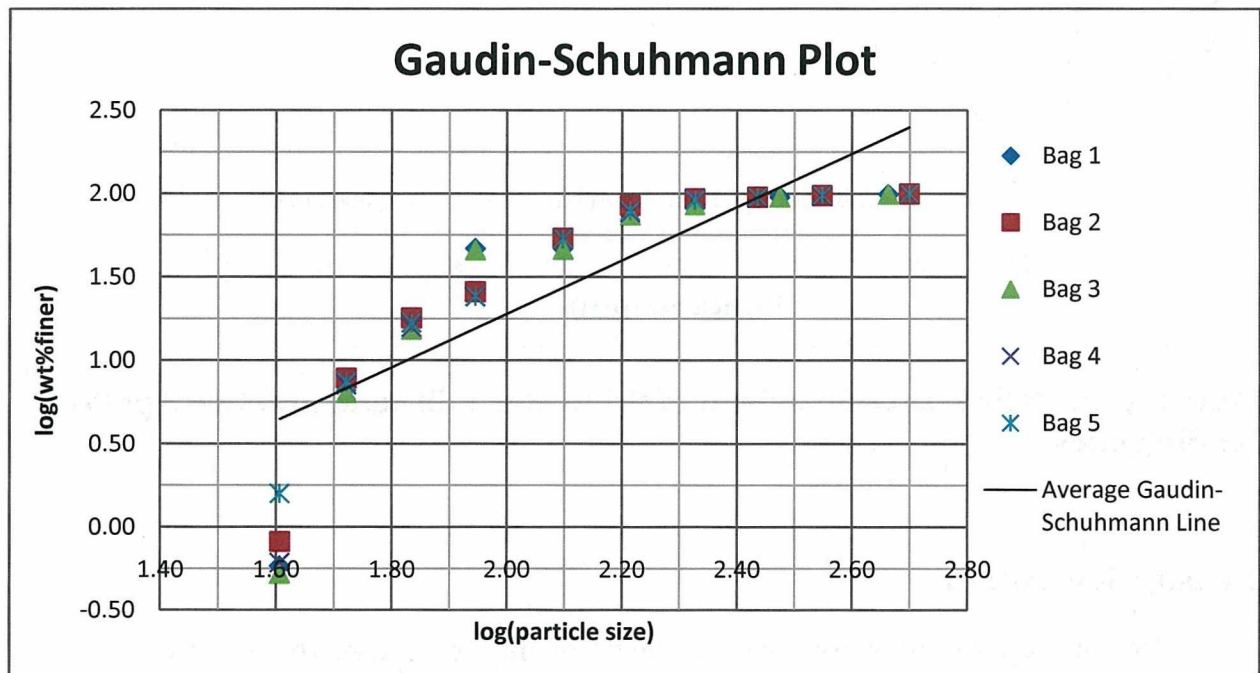


Figure 3: Particle Size Comparisons

This test was run a second time, and samples from specific sieves were collected. XRD tests were then run on the material to determine if the minerals were segregating into different size classes. The results of the XRD were, however, inconclusive. Figure 4 is a graph of the mill sand data (from Figure 3) compared to two different Apollo landing site samples. The two moon landing sites were slightly different from one another, but the range of the Stillwater Mill Sand compared to the two sites is even greater. This conclusion means that using the mill sand is not an ideal choice for this project.

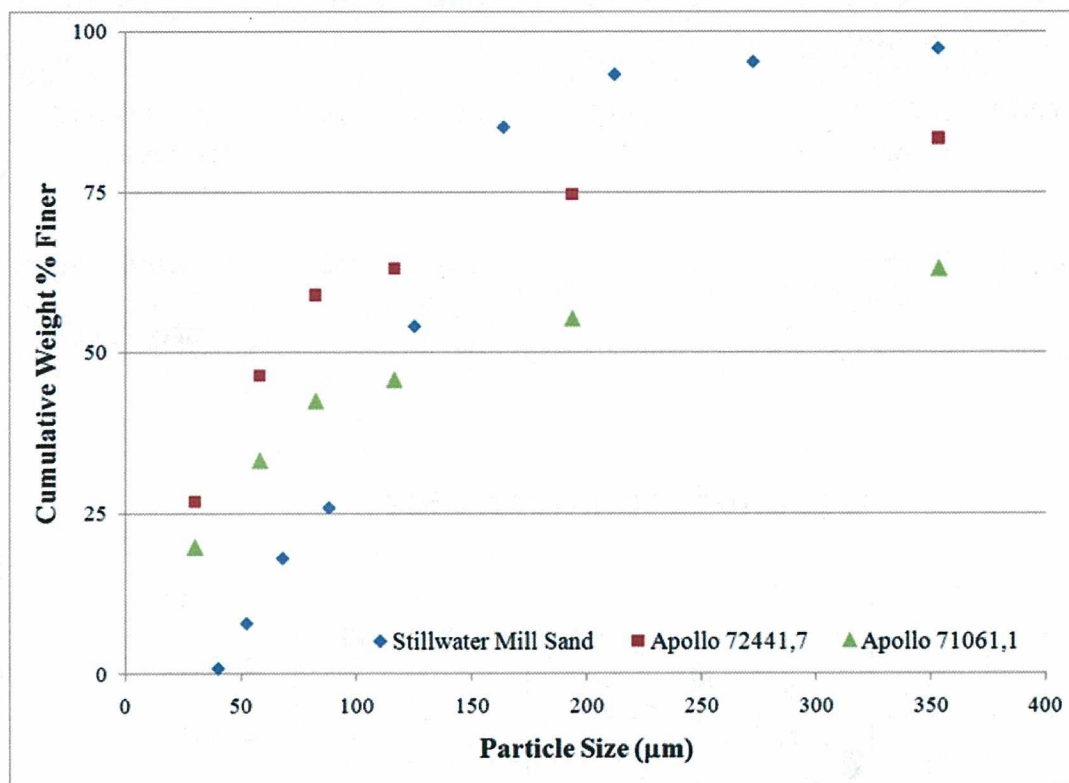


Figure 4: Particle size comparison of Stillwater mill sand and two Apollo landing sites

Density Separation

Density separation is exactly what the name implies; it uses the density differences of constituents in a mixture of materials to separate them. In general, the larger the density differences in the constituents, the easier and more feasible density separation techniques become. Also, in general, density separation takes place in a fluid

medium—namely water, air, or a particle filled fluid. Sometimes other fluids are used, but they are more expensive, especially when separating on an industrial scale. When calculating the settling velocities for the constituents in these fluid mediums, Stoke's equation is usually applied in some form. The settling velocities determine the time it takes for each constituent to settle. This is very important because the time it takes to separate the materials can be the deciding factor in whether the process is economically feasible.

There are some inherent advantages and disadvantages to using density separation as the method of separation. Density separation does not require any chemical reagents for success. This increases safety and decreases cost in most cases. Density separation is limited when trying to separate materials with similar densities, however.

Lunar Regolith Simulant Production in Relation to Density Separation

The minerals of concern for lunar regolith simulant and their densities are shown below in Table 3. The densities are given in grams per centimeter cubed.

Table 3: Densities of Consituents

Mineral	Density	Average
Pyroxenes:		
Donpeacorite (Ortho-)	3.36	3.36
Clinoenstaite (Clino-)	3.2-3.6	3.4
Plagioclase:		
Albite-	2.61-2.63	2.62
Anorthite-	2.72-2.75	2.73

It is apparent that there is an inherent problem with using density differences to separate pyroxenes by density. The densities overlap within the pyroxene minerals, making separating these materials from each other by density differences exceedingly difficult. This could be overcome by using a surface treatment to change the apparent

molecular weight of the particles to be separated. However, as the pyroxenes do have a slightly higher density than the plagioclases, it may be possible to separate these from each other.

Froth Flotation

Froth flotation is a process through which differing minerals are separated using differences in surface chemistry. Minerals are typically made to be either hydrophilic or hydrophobic based on control of such parameters as slurry pH, electro negativity, and the addition of collectors and depressants. With all of these additives, while they may use different mechanisms to get the end result, the goal is to create a condition in which one or more minerals exhibit properties different from the bulk slurry. In a typical flotation cell, the value minerals are made to be hydrophobic so that they are repelled by water and bond to air bubbles rising through the slurry. This results in their being entrained in a layer of froth on top of the slurry (a reagent known as a frother is typically needed to stabilize this froth bed and ensure that it exists for a sufficient duration for the enriched froth to be removed.) The froth is then removed as the concentrate. In a differential flotation, it is the desired minerals which are treated to become hydrophilic and so be repelled by the air bubbles and so exit in the slurry in what would be the tails stream in a normal circuit while the froth contains mostly gangue material.

After consideration of the minerals involved, it has been determined that froth flotation is unlikely to be a suitable method for separating the clino- and orthopyroxenes from each other (see Table 2). This is based on several factors. First, as the process of froth flotation relies on differences in surface chemistry, the fact that the clino- and orthopyroxenes are virtually chemically identical (the only difference being in the crystal lattice parameters) poses some difficulty in creating differing surface properties. Second, given the process by which pyroxenes form, the orthopyroxenes are typically encased in a layer of clinopyroxene, existing as a single grain with multiple crystalline structures. This second fact makes it difficult to separate the two pyroxenes without fine comminution. Third, reducing the grain size to a prohibitively small level may in itself prevent flotation as a minimum particle size is required. Furthermore, a thorough battery of tests to determine the best schedule for froth flotation would prove to be too time consuming given the limited amount of time given.

Magnetic Separation

Magnetic separation takes advantage of the magnetic properties of the material. By passing the material through a magnetic field, the attractive and repulsive forces separate the material into three groups: magnetic, diamagnetic, and magnetically neutral. This process is straightforward and simple; however, magnetic properties of the constituents are critical. A diagram of the magnetic separation process can be seen in Figure 5.

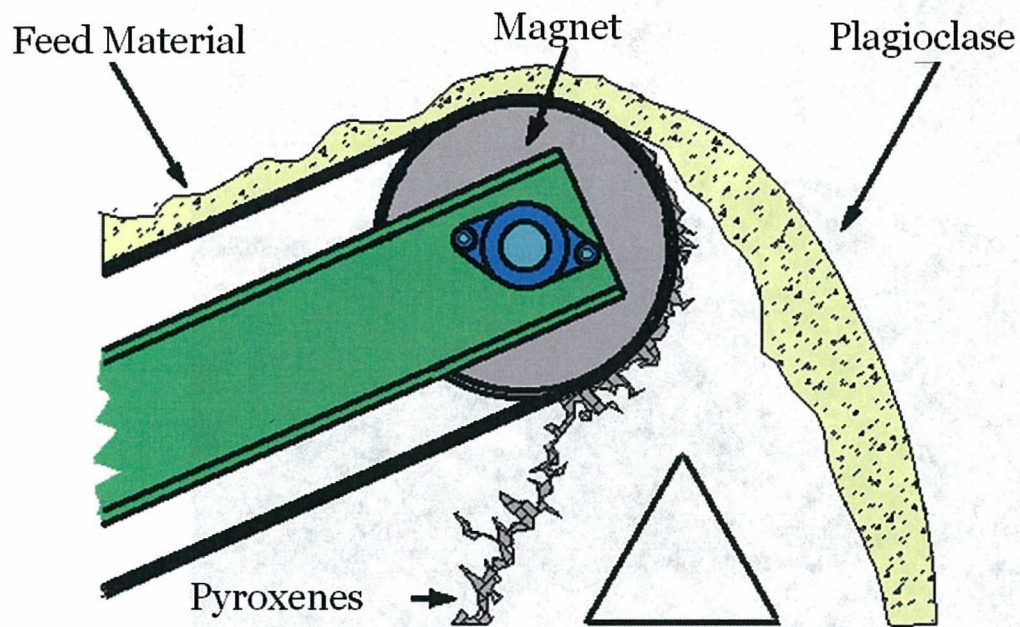


Figure 5: Diagram of Magnetic Separation

From Table 2, it is clear that plagioclase ($\text{NaAlSi}_3\text{O}_8$ - $\text{CaAl}_2\text{Si}_2\text{O}_8$) is diamagnetic, while pyroxenes ($\text{Ca}(\text{Mg},\text{Fe})\text{Si}_2\text{O}_6$; $(\text{Mg},\text{Fe})_2\text{Si}_2\text{O}_6$) are expected to be paramagnetic (weakly magnetic). Further, if the material is paramagnetic, more powerful magnetic fields are required, and the costs to generate these more powerful magnetic fields can quickly escalate. Separation tests were performed on the road norite and mill sand using a Frantz Isodynamic Separator (see Figure 6). In both materials the darker-colored pyroxene minerals were separated from the lighter-colored plagioclase. However, x-ray diffraction analysis performed on the separated mill sand was inconclusive. This was due to the complex composition of the mills and, the extent of which was unknown at the time the test was performed.



Figure 6: Frantz Isodynamic Separator

While the Frantz Isodynamic Separator was useful for small samples, the rate of separation was far too slow economically for mass quantities. A second magnetic separation experiment was performed using an Eriez Rare Earth Roll magnetic separator, located at Pacer Corp. in Custer, SD. Two gallons of road norite were roll crushed and passed through the separator twice. The separates were then sieved, and x-ray diffraction analysis was performed. The results of the magnetic separation are displayed in Table 4. As the table shows, 100% separation between the plagioclase and pyroxenes was achieved up to +400 mesh size.

Table 4: Magnetic Separation Results

Mesh Size	Material	Wt % Plagioclase	Wt % Orthopyroxene	Wt % Clinopyroxene	Wt % Talc	Wt % Calcite
+28, -45	Magnetic	-	94.6	4.0	1.4	-
	Nonmagnetic	96.9	-	-	-	3.1
+45, -80	Magnetic	-	87.8	10.7	1.5	-
	Nonmagnetic	96.6	-	-	-	3.4
+140, -200	Magnetic	-	82.1	14.5	3.4	-
	Nonmagnetic	98.2	-	-	-	1.8
+400	Magnetic	37.2	44.8	8.0	10.0	-
	Nonmagnetic	95.1	-	-	-	4.9

Electrostatic Separation

One method of separation our group examined was free-fall electrostatic separation. In electrostatic separation, the media is fed through a rotating tube. As the tube rotates, the particles will rub against each other causing static charges to build. The particles fall through an opening and are subject to a high-potential low amperage field. This field will move the positively charged particles towards the negative electrode and vice-versa.

With the success of magnetic separation in separating the plagioclase from the pyroxenes in the road norite, a method for separating the pyroxenes electrostatically was needed. As there was no suitable separator on campus, a design was created that would allow for several variables to be adjusted. The design of the separator allows for the adjustment of retention time in the tube which will tumble the minerals, adjustment of the amount of tumbling in the tube, and the voltage between the charged plates.

While initial tests of the separator showed that it was functional, the power supply failed quickly thereafter. As a result, repairs need to be made before any actual tests of the separator's effectiveness in separating the pyroxenes. Additionally, a manual on the operation and care of the separator as well as schematics need to be created.

Global and Societal Context

A successful design will assist in global understanding and ability to construct long-term bases on the lunar surface. Such bases would have far reaching effects on future space travel and discoveries. Ethical concerns may exist over acquisition of the road norite. Ownership issues and availability may be a future concern. This is a global issue as Canada, the United States, Japan, Germany, and South Africa were all working together to create a simulant. Because Canada and South Africa have reasonable ores for similar regolith simulant, when more people produce their own, it would promote international and commercial participation.

Some of the constellation objectives of this design are: to extend human presence across the solar system (i.e. moon, mars, asteroids); to develop innovative technologies, knowledge and infrastructures, both to explore and to support decisions about the destinations for human exploration; and to promote international and commercial participation in exploration to further the United States' scientific, security, and economic interests.

Lessons Learned

Having a group this large, there should have been better group management, communication, and personal accountability. Having the sample arrive in late November put a damper in things, but as soon as the sample was received, the magnetic separation could have begun, along with the construction of the electrostatic separator.

Conclusion

Initially, Dr. Rickman expressed NASA's interest in the mill sand over the road norite. Mill sand is available in ready supply and is already crushed. As comminution can be up to half the cost of most mining processes, this would have great economic advantage. However, analysis of the mill sand revealed small percentages of the desired plagioclase and pyroxene minerals and a great deal of inclusion of extraneous materials from the mining process. In contrast, analysis of the road norite displayed high percentages of plagioclase and pyroxenes, with little non-desired material. While some level of comminution is still required, magnetic separation results showed full liberation of the pyroxenes from the plagioclase. The next phase of the project will be to investigate separating the clinopyroxenes and orthopyroxenes, specifically by means of electrostatic separation.